US009473337B2

(12) United States Patent
Thursby et al.

(10) Patent No.: US 9,473,337 B2
(45) Date of Patent: Oct. 18, 2016

(54) CARRIER RECOVERY IN A QAM RECEIVER

(71) Applicant: **E.V. Offshore Limited**, Norwich (GB)

(72) Inventors: **Jonathan Thursby**, Norfolk (GB); **Sumanth Eadala**, Hethersett (Norwich) (GB)

(73) Assignee: **E.V. Offshore Limited**, Norwich (GB)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/769,672**

(22) PCT Filed: **Feb. 28, 2014**

(86) PCT No.: **PCT/IB2014/059341**
§ 371 (c)(1),
(2) Date: **Aug. 21, 2015**

(87) PCT Pub. No.: **WO2014/132238**
PCT Pub. Date: **Sep. 4, 2014**

(65) **Prior Publication Data**

US 2016/0006590 A1 Jan. 7, 2016

(30) **Foreign Application Priority Data**

Feb. 28, 2013 (GB) 1303623.1

(51) **Int. Cl.**
H04L 27/06 (2006.01)
H04L 27/38 (2006.01)
H04L 27/227 (2006.01)

(52) **U.S. Cl.**
CPC ***H04L 27/066*** (2013.01); ***H04L 27/2273*** (2013.01); ***H04L 27/3872*** (2013.01)

(58) **Field of Classification Search**
CPC H04L 27/066; H04L 27/2273; H04L 27/3872
See application file for complete search history.

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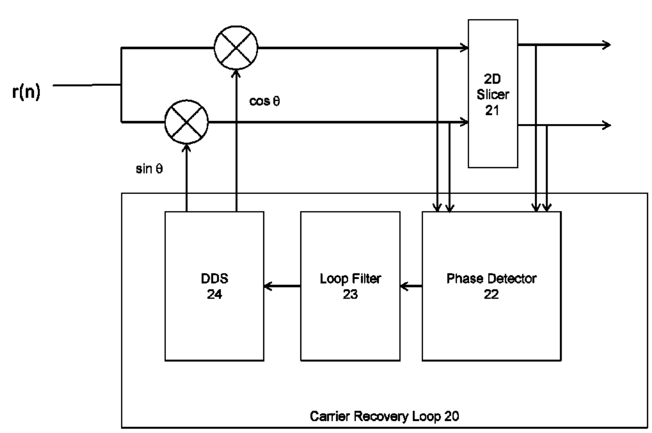
Primary Examiner — Ross Varndell
(74) *Attorney, Agent, or Firm* — Hayes Soloway, P.C.

(57) **ABSTRACT**

The present invention relates to inspection apparatus for use in wellbores in the oil and gas industries. In particular the invention relates in general to the field of transmission of data between downhole module in a wellbore and a controlling module at the surface. The invention provides a method an apparatus for receiving data from a telemetry module, the data being modulated according to a quadrature amplitude modulation coding scheme, in which a receiver has a carrier recovery circuit comprising a phase detector, a loop filter and a signal synthesizer generating an inphase and a quadrature demodulation signal. The method comprises receiving a preamble sinusoidal signal representing a symbol; determining the cross product of the received inphase and quadrature components and ideal inphase and quadrature components; indexing a look up table with said cross product to determine a phase adjustment and adjusting the phase of the demodulation signals in accordance with said determined phase adjustment.

16 Claims, 9 Drawing Sheets



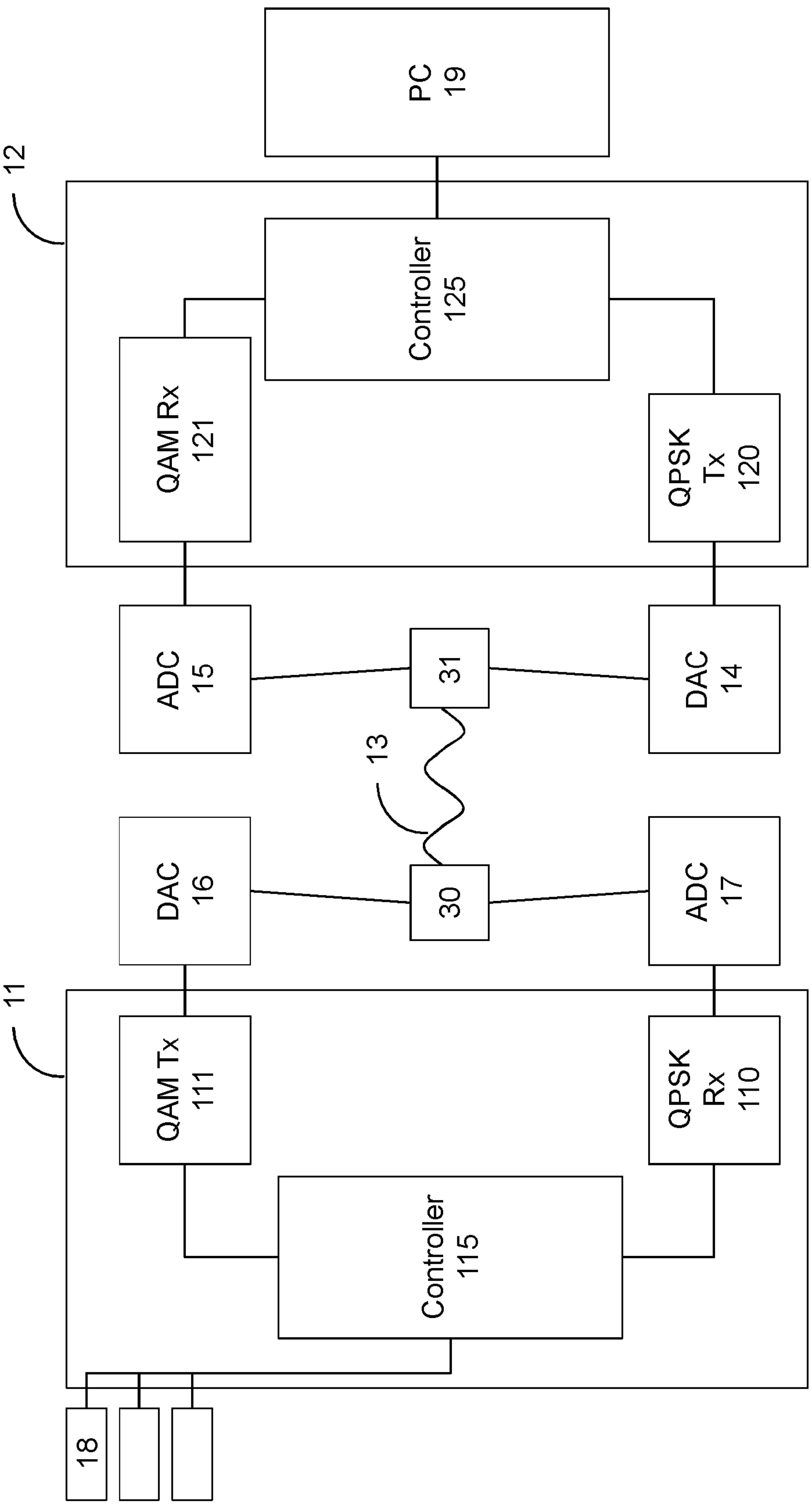

PC
19
12
Controller
125
QAM Rx
121
QPSK
Tx
120
ADC
15
31
DAC
14
13
DAC
16
30
ADC
17
11
QAM Tx
111
QPSK
Rx
110
Controller
115
18

Figure 1

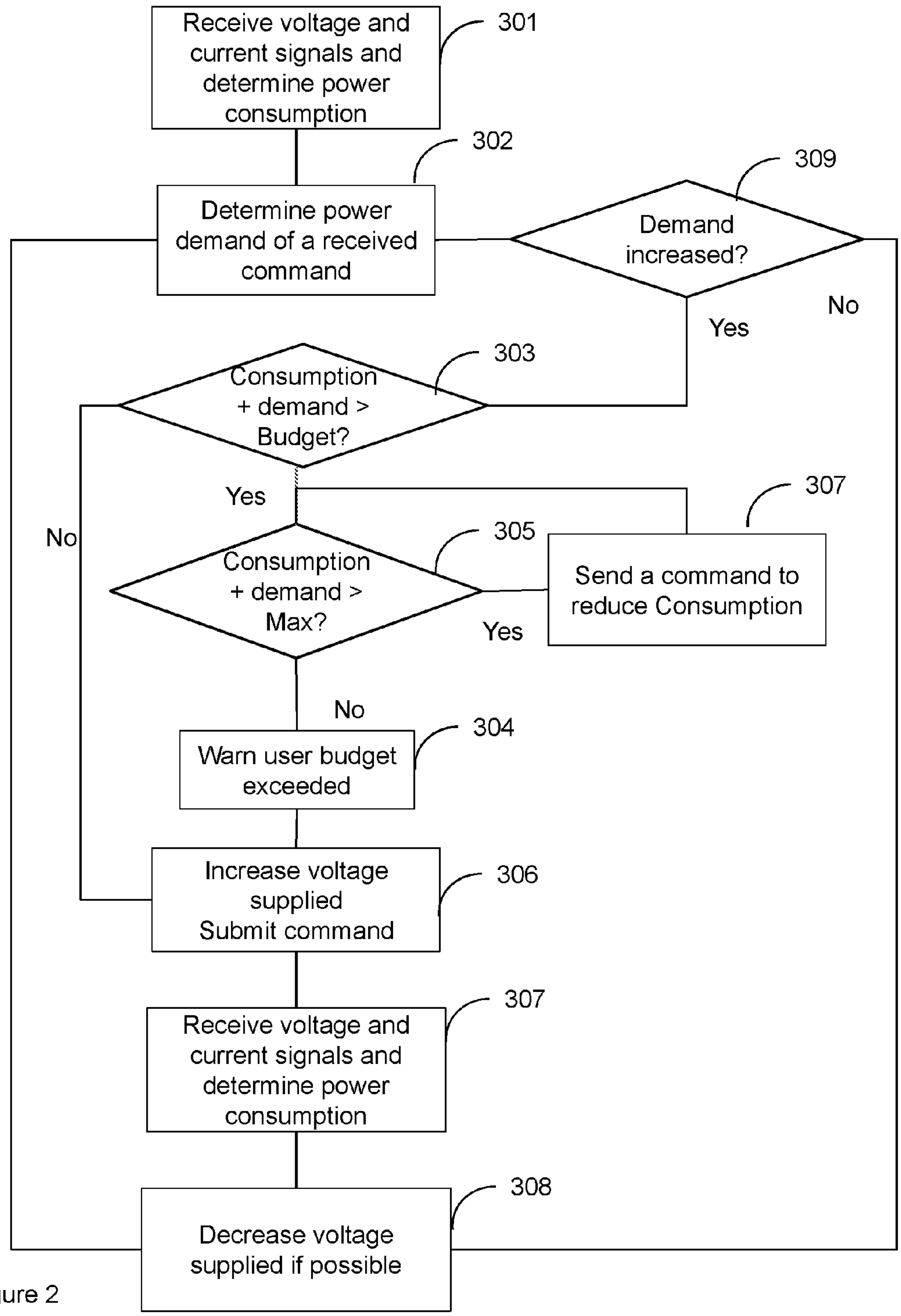

Receive voltage and current signals and determine power consumption
301
302
Determine power demand of a received command
309
Demand increased?
No
Yes
303
Consumption + demand > Budget?
Yes
307
No
305
Consumption + demand > Max?
Send a command to reduce Consumption
Yes
No
304
Warn user budget exceeded
Increase voltage supplied
Submit command
306
307
Receive voltage and current signals and determine power consumption
308
Decrease voltage supplied if possible

Figure 2

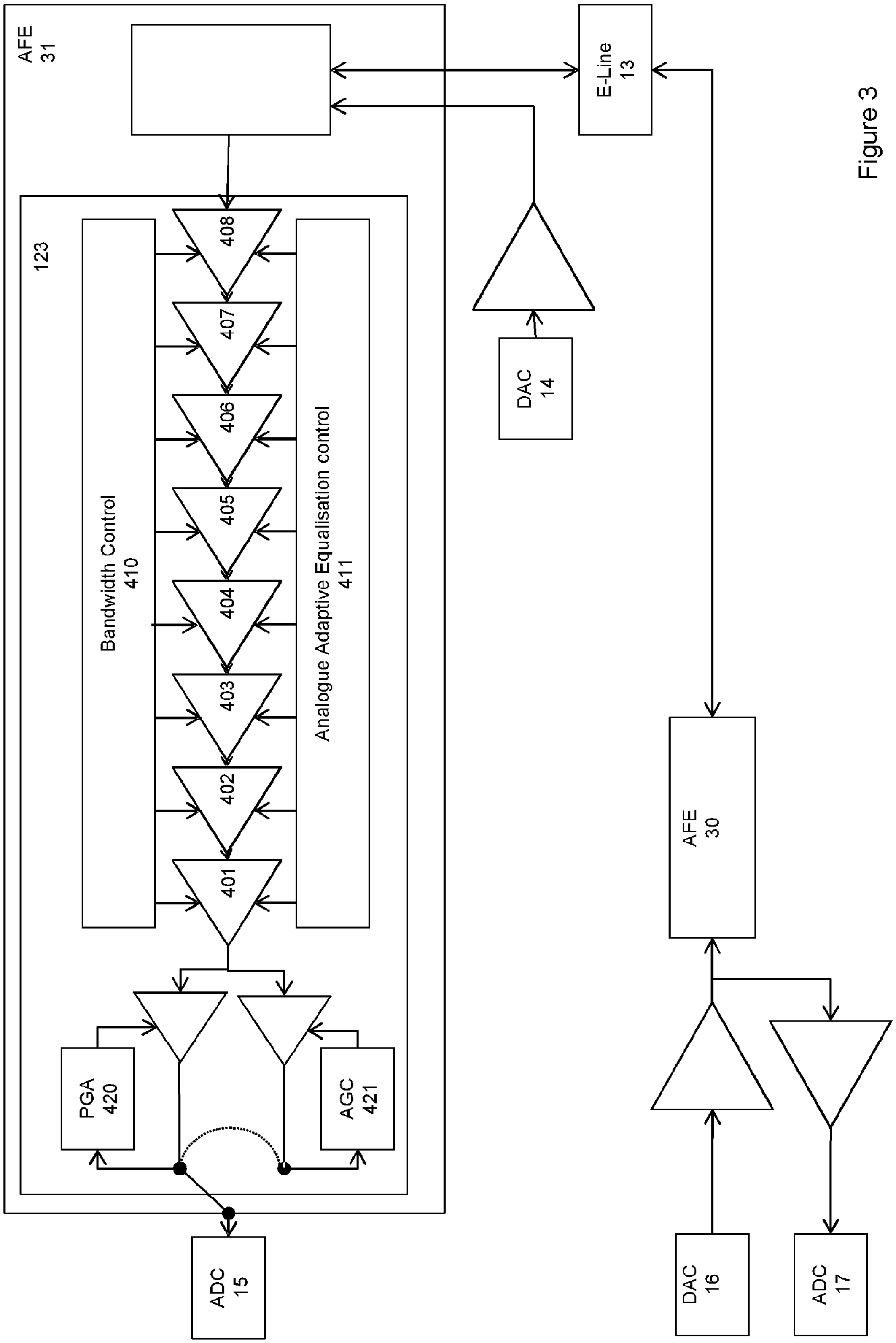

AFE
31
E-Line
13
123
408
407
406
405
404
403
402
401
Bandwidth Control
410
Analogue Adaptive Equalisation control
411
DAC
14
PGA
420
AGC
421
ADC
15
AFE
30
DAC
16
ADC
17

Figure 3

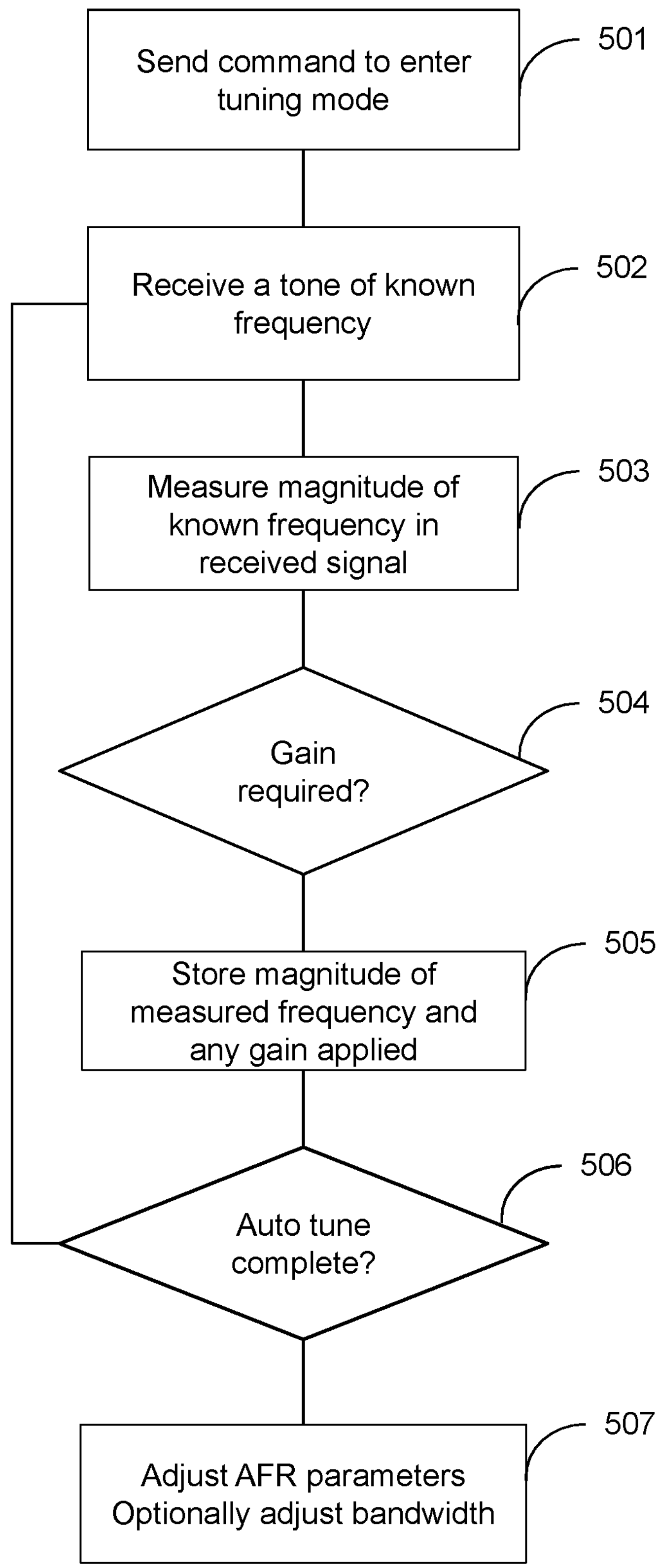

Send command to enter tuning mode
501
Receive a tone of known frequency
502
Measure magnitude of known frequency in received signal
503
Gain required?
504
Store magnitude of measured frequency and any gain applied
505
Auto tune complete?
506
Adjust AFR parameters Optionally adjust bandwidth
507

Figure 4

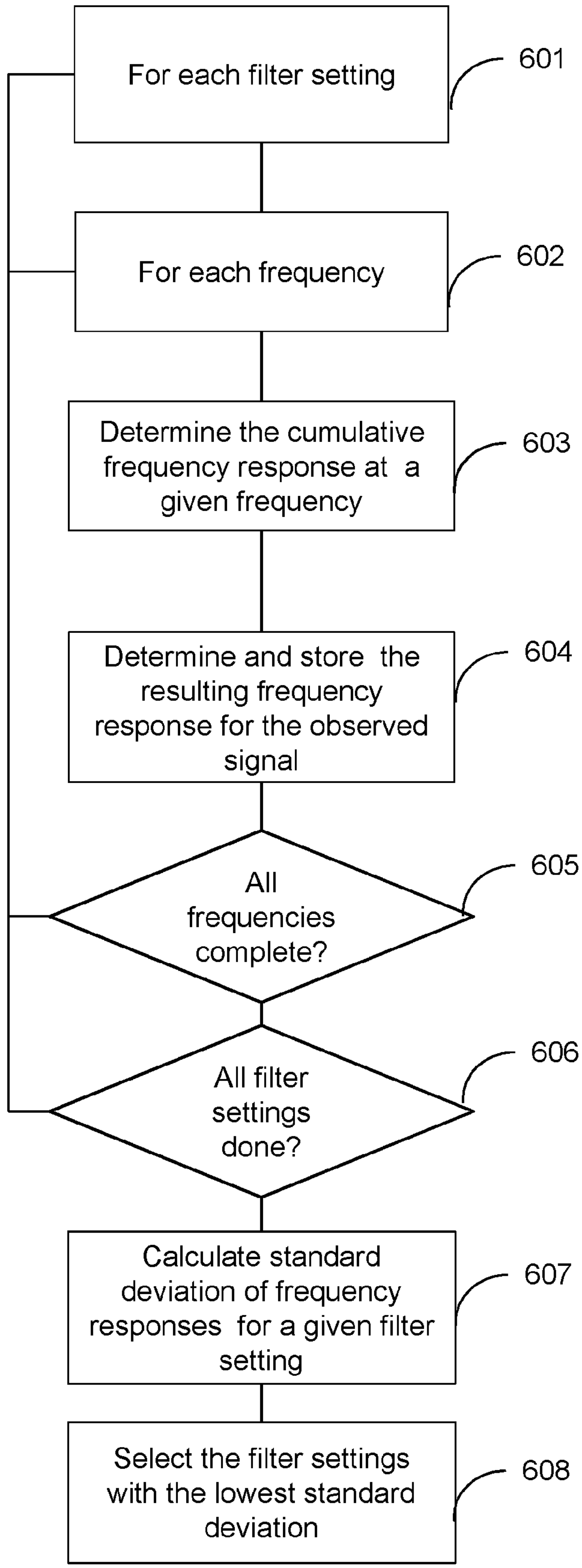
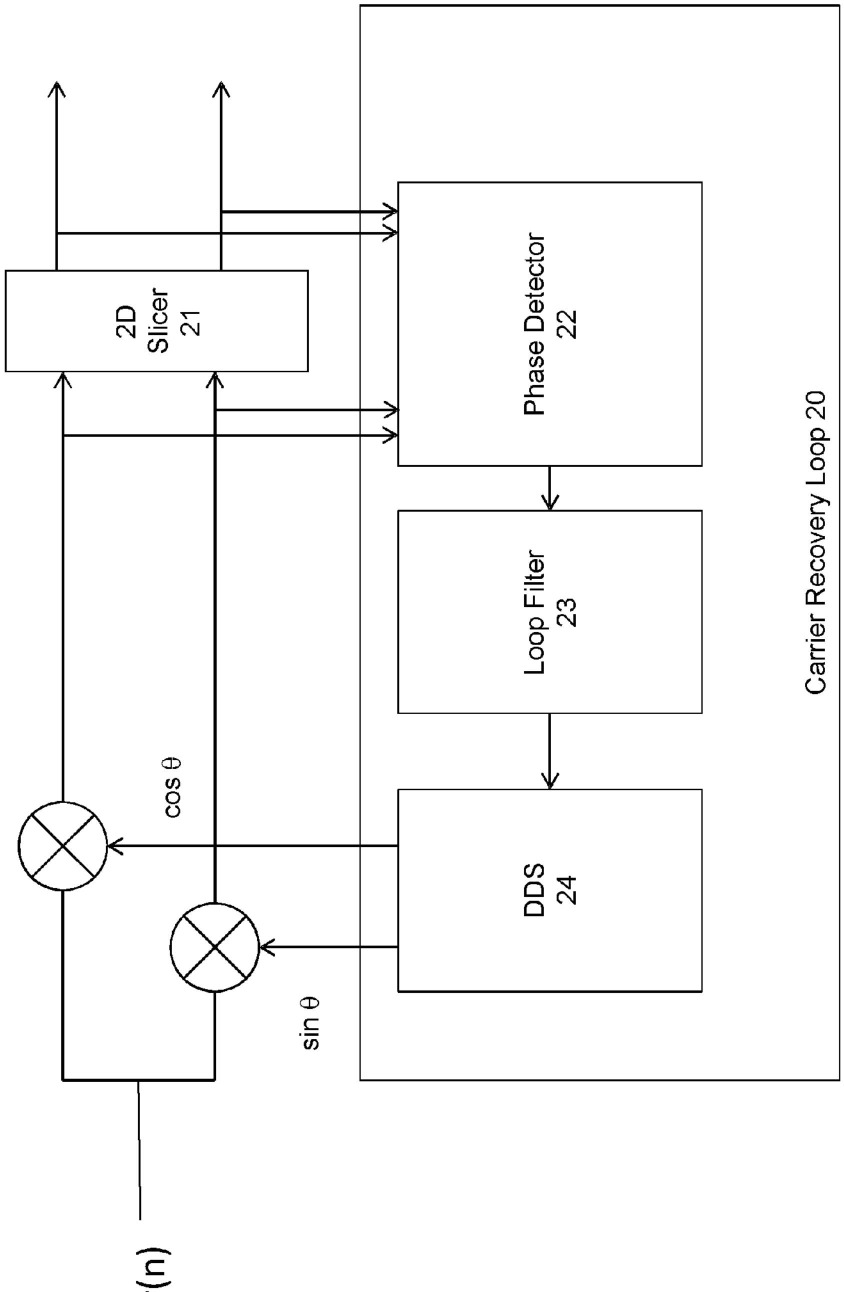

For each filter setting
601
For each frequency
602
Determine the cumulative frequency response at a given frequency
603
Determine and store the resulting frequency response for the observed signal
604
All frequencies complete?
605
All filter settings done?
606
Calculate standard deviation of frequency responses for a given filter setting
607
Select the filter settings with the lowest standard deviation
608

Figure 5



2D Slicer 21
Phase Detector 22
Loop Filter 23
DDS 24
Carrier Recovery Loop 20
cos θ
sin θ
r(n)

Figure 6

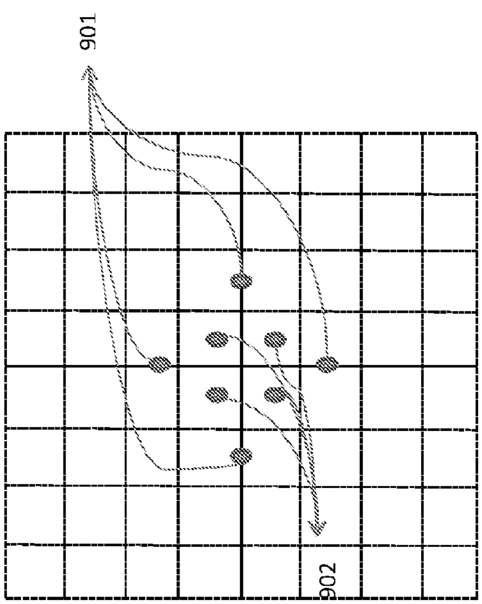


Figure 7a example of 8 point QAM

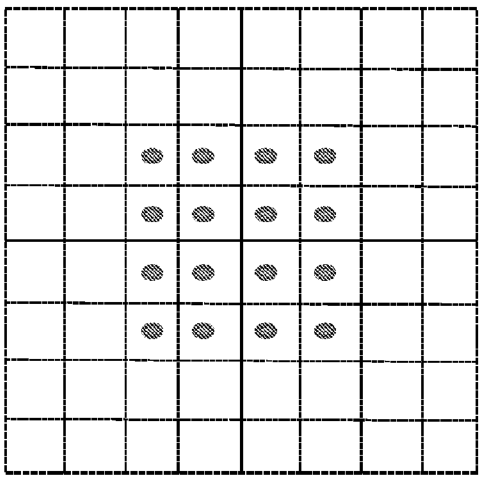


Figure 7b example of 16point QAM

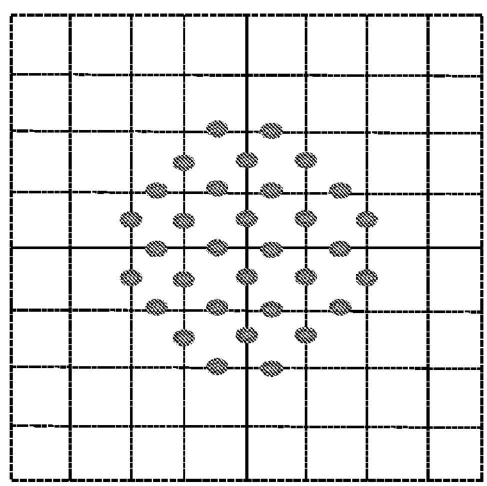


Figure 7c example of 32 point QAM

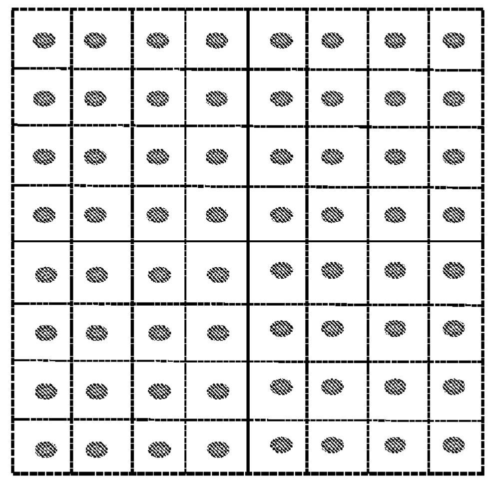
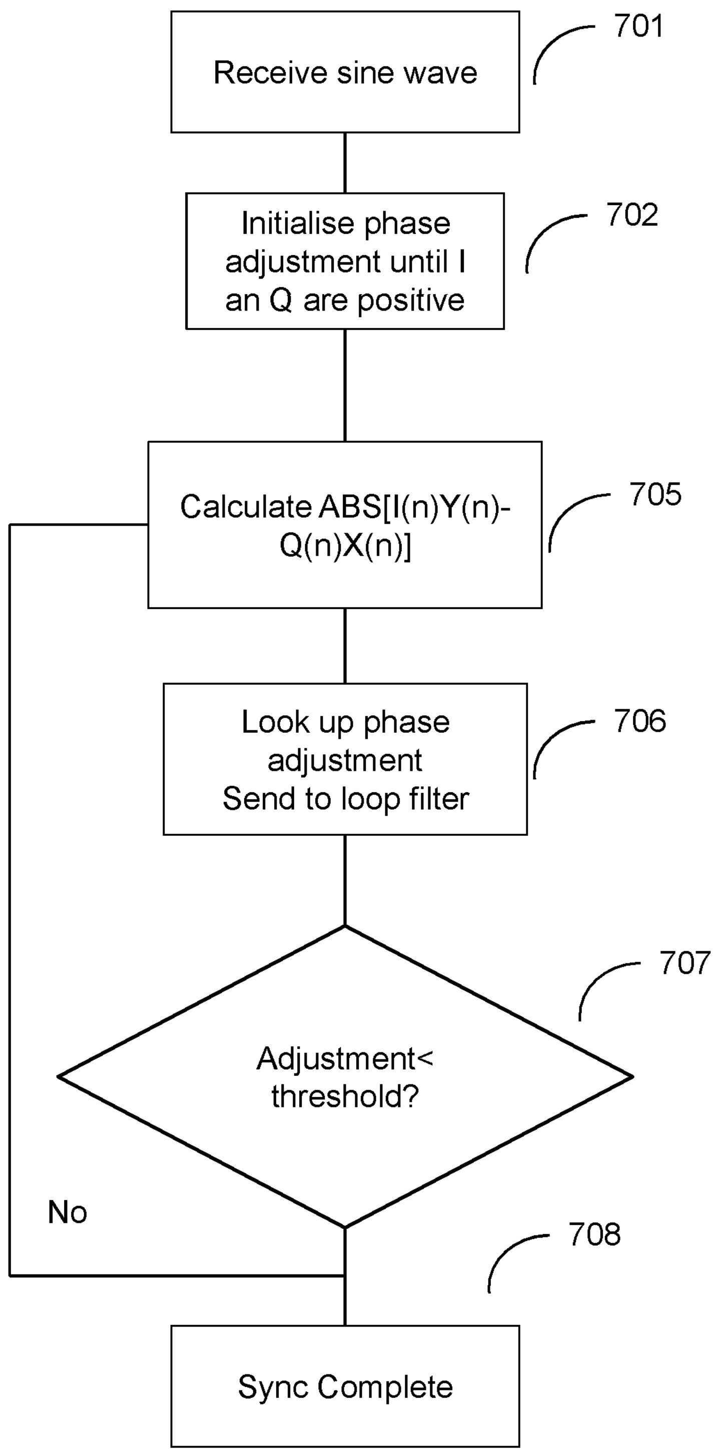


Figure 7d example of 64 point QAM



Receive sine wave
701
Initialise phase adjustment until I an Q are positive
702
Calculate ABS[I(n)Y(n)-Q(n)X(n)]
705
Look up phase adjustment
Send to loop filter
706
Adjustment< threshold?
707
No
708
Sync Complete

Figure 8

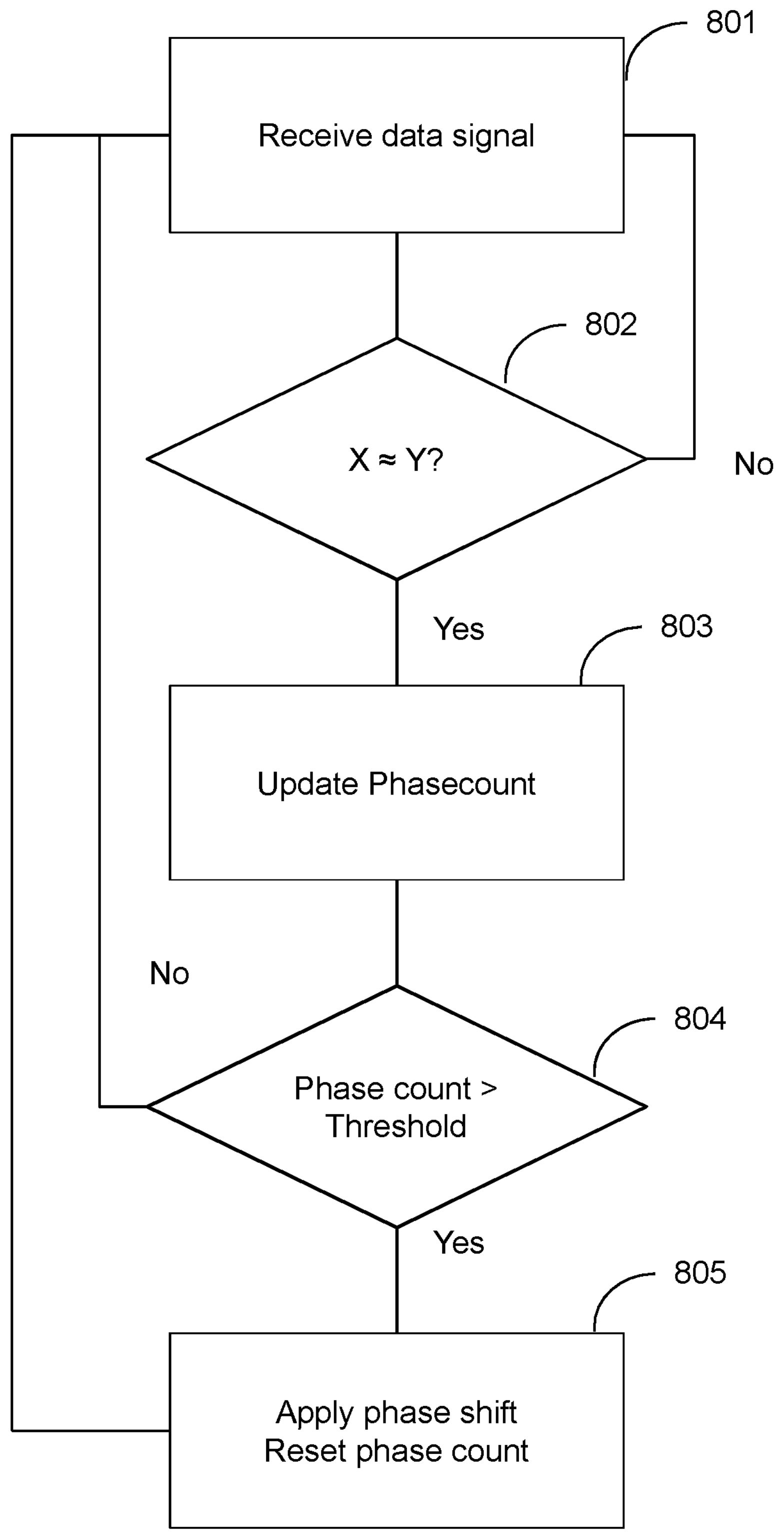

801
Receive data signal
802
X ≈ Y?
No
Yes
803
Update Phasecount
No
804
Phase count > Threshold
Yes
805
Apply phase shift
Reset phase count

Figure 9

CARRIER RECOVERY IN A QAM RECEIVER

BACKGROUND

a. Field of the Invention

The present invention relates to inspection apparatus for use in wellbores in the oil and gas industries. In particular the invention relates in general to the field of transmission of data between downhole module in a wellbore and a controlling module at the surface.

b. Related Art

Accurate collection of geophysical data is a key to successful exploration and production in oil and gas industries. Based on data collected in a wellbore it is possible to determine whether a well is likely to be productive, and decisions can be made such as whether to drill additional wells near an existing well or whether to abandon a well as being unproductive.

Collecting wellbore data is known as well-logging. In well-logging, a telemetry module is lowered into a wellbore on a cable containing an inner core of insulated wire known as a wireline cable. The wireline cable provides power to equipment located at the end of the cable, and provides a pathway for electrical telemetry for communication between the surface and the telemetry module at the end of the cable.

The telemetry module is an electrically powered measurement device for inspecting the wellbore and is connected to a surface controller via the wireline cable.

Electrical digital and data control signals are transmitted between the surface controller and the downhole telemetry module via one or more conductors in the wireline cable. Downstream data signals are used to remotely control the functions of various downhole devices such as one or more cameras, motor tools to rotate a part of the module and to configure parameters for sensors such as temperature & pressure sensors, accelerometers and gyroscopes.

Upstream data signals transmit information from the telemetry module to the controller such as images, information indicative of the operation of the downhole devices or parameters detected or measured by the sensors.

The wellbore depth and hence the distance between the telemetry module and the surface controller may be many thousands of feet. Temperatures in the wellbore may rise to over 100 degrees Centigrade. The wireline cable must be designed to withstand the physical conditions and to sustain the weight of the telemetry module complete with tools connected beneath it and the length of the wireline cable as the telemetry module is lowered into the wellbore. The wireline cable is not primarily designed as a communications channel for efficiently transmitting modulated data signals and therefore the channel frequency response of the cable is not optimised for efficient data transmission.

Modulated data signals require synchronisation between the transmitter and receiver clocks in order to code and decode the data signal effectively. One problem with high temperature operation is that clock drift and hence synchronisation becomes more of an issue. Clocks usually vary by up to 10 ppm but at temperatures of 125° C. this can raise to 25-50 ppm. Also the signal attenuation at high frequency is much greater that at low frequencies.

U.S. Pat. No. 5,838,727 discloses a method and apparatus for transmitting and receiving acquired digital data over narrow bandpass channels with high signal to noise ratios and at high temperatures using quadrature amplitude modulation techniques.

However, maintaining clock synchronisation under these circumstances is difficult.

The present invention uses a novel QAM technique to maintain clock synchronisation.

SUMMARY OF THE INVENTION

According to the invention there is provided a method and apparatus for receiving data from a telemetry module, the data being modulated according to a quadrature amplitude modulation coding scheme, in which a receiver has a carrier recovery circuit comprising a phase detector, a loop filter and a signal synthesiser generating an inphase and a quadrature demodulation signal, the method comprising the steps of: a) receiving a preamble sinusoidal signal representing a symbol; b) matching the phase of the inphase signal generated by the signal synthesiser to the phase of the received signal; c) matching the phase of the quadrature signal generated by the signal synthesiser to be ninety degrees out of phase the phase with the received signal; d) repeating the step of determining whether the received signal represents a symbol having positive inphase and quadrature components; in the event the components are not both positive, adjusting the phase of the inphase and quadrature components by a fixed phase shift until the received signal represents a symbol having positive inphase and quadrature components; e) determining the cross product of the received inphase and quadrature components and ideal inphase and quadrature components f) indexing a look up table with said cross product to determine a phase adjustment and g) adjusting the phase of the demodulation signals in accordance with said determined phase adjustment.

Preferably steps e) to g) are repeated until the phase adjustment is less than a predetermined minimum. Advantageously said predetermined minimum is 0.5 degrees.

The preamble signal is preferably a sinusoidal signal representing a symbol in the encoding scheme having the greatest signal to noise ratio.

The lookup table is sparsely populated to reduce memory use and comprises entries for unequally spaced phase differences with entries close together for small phase differences and entries further apart for greater phase differences.

It is an advantage to adjust for small phase rotations due to frequency fluctuations by h) determining whether the received signal represents a symbol having equal inphase and quadrature components i) in the event the received signal represents a symbol having equal inphase and quadrature components, updating a phase difference measure in dependence upon the difference between the magnitude of the inphase and quadrature component of the received signal; and j) adjusting the phase of the signals generated by the signal synthesiser when said phase difference measure exceeds a predetermined threshold.

In a preferred embodiment the phase difference measure is updated at step i) by incrementing the phase difference measure by one if a first one of the components is greater than a second one of the components and by decrementing the phase difference measure by one if the second one of the components is greater that the first one of the components. Preferably the predetermined threshold is set to fifteen and the phase adjustment applied is 0.5 degrees.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described, by way of example only, with reference to the accompanying drawings in which:

FIG. **1** is a block diagram illustrating a telemetry module and a surface controller connected via a wireline cable.

FIG. **2** is a flow chart illustrating power optimisation according the present invention;

FIG. **3** is a block diagram showing an analogue adaptive equaliser for use in the present invention;

FIG. **4** is a flow chart illustrating an autotuning process;

FIG. **5** is a flow chart illustrating a method of determining optimum parameters.

FIG. **6** is a block diagram of a quadrature amplitude modulation (QAM) receiver for use in a controller of the present invention;

FIG. **7** is an illustration of QAM constellations;

FIG. **8** is a flow chart illustrating a method used to lock to the phase of generated carrier signals to the phase of the received signal; and

FIG. **9** is a flow chart illustrating a method for determining small phase adjustments to maintain frequency lock.

DETAILED DESCRIPTION

Referring now to FIG. **1** a telemetry module **11** is connected to a surface controller **12** via a wireline cable **13**. Data is sent from the controller to the module via a quadrature phase shift keying (QPSK) link. Data is sent from the module to the controller via a quadrature amplitude modulation (QAM) link. Controller **12** is connected to a computer **19** which is used to send commands to the controller **12** for controlling the various downhole devices such as one or more cameras, motor tools to rotate a part of the module and to configure parameters of sensors such as temperature sensors, pressure sensors, gyroscopes and accelerometers.

The surface controller **12** has a QPSK transmitter **120** and a QAM receiver **121**. Downstream communication from the controller to the telemetry module is a low data rate (1000 baud) and is sent over the QPSK link by the QPSK transmitter **120**. A digital signal from the QPSK transmitter **120** is converted to an analogue signal by a digital to analogue converter **14** for transmission via the wireline cable **13**.

Upstream signals received from the telemetry unit to the controller are converted to a digital QAM signal by analogue to digital converter **15** and received by the QAM receiver **121** via an analogue adaptive equaliser **123** which will be described later with reference to FIG. **3**

For example commands may be sent to the telemetry module to control the resolution and frame rate of images sent by cameras, or the compression ratio of the image data. A high frame rate may be compensated by a lower resolution and vice versa. Commands may also be used to switch between camera data feeds where there is more than one camera. Alternatively, two streams may be sent simultaneously, alternating between cameras resulting in a lower frame rate and/or lower resolution in each stream. Commands may also be used to control the lighting or the rotation of the inspection apparatus.

The telemetry module **11** has a QAM transmitter **111** and a QPSK receiver **120**. Upstream communication from the telemetry module to the surface controller is video data (encoded using H264/MPEG-4), along with telemetry data at a total data rate of 200 Kbits/s and is sent over the QAM link by the QAM transmitter **111**. A digital signal from the QAM transmitter is converted to an analogue signal by a digital to analogue converter **16** for transmission via the wireline cable **13**.

Downstream signals from the controller to the telemetry unit are converted to a digital QPSK signal by analogue to digital converter **17** and are received by the QPSK receiver **110**.

The telemetry module is powered via the wireline cable **13** (also known as E-line) using a proprietary power line communication protocol. The surface controller **12** receives sensor data from sensors **18**, which may include temperature data, and voltage and current data from the telemetry module **11**. The sensor data is sent via the QAM receiver **121** to the controller **125**. In response the controller **125** adapts the power transmitted to the module in order to decrease the temperature and/or increase the cooling when necessary.

Controller **125** continually monitors voltage/current feedback via telemetry data fed back from controller **115** and adjusts the voltage to optimise the load and thus limit heat generation within power supply of downhole telemetry module **11**.

FIG. **2** is a flow chart illustrating a power optimisation system according to the present invention.

At step **301** the surface controller **125** receives voltage and current signals from the telemetry unit controller **115** and determines the power consumption

A total power budget is predetermined for the system. Before a control message is sent from Controller **125** to Controller **115**, the power demand likely to be caused by execution of the command is determined at step **302**

If it will cause more power demand at step **309** e.g. increase camera light level, rotate motor then if the power consumption plus the anticipated demand is less that the predetermined budget at step **303**, then the Controller **125** increases the voltage, (to slightly more than the anticipated demand) at step **306**, within the total budget to allow for the new demand, the controller **125** then waits for a short time for the signals to settle and then submits the command message to controller **115** which performs the requested function.

The budget can be exceeded resulting in additional heat being dissipated in the telemetry unit **11**, but only up to a maximum physical limit which depends upon the resistance of the cable and the power supply unit capabilities.

If the power consumption plus the anticipated demand is less than (or equal to) the physical maximum at step **305**, then the user of system is warned at step **304** and should try to execute one or more commands to reduce the demand as soon as possible, for example the user may choose to lower the light levels.

If the power consumption plus the anticipated demand is greater than that the physical maximum at step **305**, then a command is sent to reduce consumption, for example, a command may be sent to turn lights down if the desired command is to send a command to rotate a camera.

The power will reset after the function is complete (i.e. motor rotation) or light levels set to lower level etc. This happens after the next volt/current telemetry data is received at step **307** when the power supplied will be reduced if the consumption has fallen.

In addition, feedback from one or more temperature sensors **18** is used within the telemetry tool to control active cooling to further reduce the temperature. Temperature data is also sent to controller **125** which can be used to further optimise the power load.

A problem with communications via the E-line is that the channel frequency response (CFR) (due to the capacitance and resistance) of the cable varies with the quality of the cable, with the overall length of the cable and also as the cable unrolls.

The analogue front end (AFE) **31** at the surface end of the E-line connector **13** provides adaptive filtering. The AFE **31** provides an analogue adaptive filter **123** and an FPGA in the controller **125** provides a digital adaptive filter to provide rapid equalisation to match the CFR. It is possible; to control the analogue filters manually, the digital adaptive filter adapts automatically. In the present invention known data is sent from the telemetry module **11** to the controller **12** in order to allow the analogue filters to adjust automatically, this process is known as autotuning.

The analogue adaptive filter **123** is shown in more detail in FIG. **3**.

The analogue adaptive filter **123** comprises a number of filter stages **401** . . . **408** which each of which can have a bandwidth and gain set via the bandwidth control module **410** and the analogue adaptive equalisation control module **411**.

settings for the stage to achieve the closest response match from the frequency and gain values stored. This results in the optimum CFR for the system.

Each filter stage **401** . . . **408** is controlled by switches which switch in and out banks of capacitance to alter the frequency response of that stage.

The frequency response for each switch setting is precalculated and stored in a lookup table, for example the table below shows the precalculated frequency response table for filter stages **401** to **406**. The frequency response figures are shown in dB so the cumulative filter frequency response from a sequence of stages may be determined by summing the values shown in the relevant tables.

In an alternative embodiment the cumulative filter frequency response from a sequence of stages may be precalculated and stored in a table resulting in higher memory usage but less processing time.

	BIN							
kHz	000	001	010	011	100	101	110	111
10	0.0000	0.2897	0.1090	0.5296	0.0470	0.4109	0.1935	0.6786
15	0.0000	0.6253	0.2446	1.1060	0.1093	0.8701	0.4258	1.3870
20	0.0000	1.0402	0.4107	1.7849	0.1861	1.4200	0.7126	2.1965
25	0.0000	1.5052	0.6115	2.4933	0.2798	2.0176	1.0470	3.0240
30	0.0000	1.9986	0.8456	3.2099	0.3923	2.6322	1.4177	3.8374
35	0.0000	2.4901	1.0849	3.8897	0.5092	3.2309	1.7876	4.5985
40	0.0000	2.9723	1.3364	4.5335	0.6386	3.8018	2.1663	5.2993
45	0.0000	3.4314	1.5885	5.1272	0.7662	4.3450	2.5365	5.9414
50	0.0000	3.8708	1.8395	5.6772	0.9004	4.8459	2.8936	6.5300
55	0.0000	4.2797	2.0805	6.1765	1.0343	5.3099	3.2338	7.0652
60	0.0000	4.6568	2.3165	6.6352	1.1657	5.7342	3.5543	7.5438
65	0.0000	5.0149	2.5438	7.0588	1.2980	6.1302	3.8588	7.9900
70	0.0000	5.3383	2.7543	7.4359	1.4200	6.4890	4.1394	8.3870
75	0.0000	5.6432	2.9601	7.7857	1.5433	6.8193	4.4023	8.7479
80	0.0000	5.9223	3.1475	8.1027	1.6577	7.1218	4.6466	9.0794
85	0.0000	6.1761	3.3263	8.3916	1.7656	7.3956	4.8720	9.3800
90	0.0000	6.4175	3.4976	8.6584	1.8742	7.6541	5.0858	9.6590

The QAM ADC **15** switches between receiving the signal via a programmable gain amplifier (PGA) circuit **420** and an automatic gain control (AGC) **421** circuit depending upon whether the circuit is in normal or tuning mode.

To optimise the AFE filter stages **410** . . . **408** to achieve the best channel frequency response, a tuning sequence can be carried out at any time.

Referring now to FIG. **4**, the controller **125** sends a command to controller **115** to enter tuning mode at step **501**. Controller **125** then sends commands to controller **115** to cause telemetry controller **115** to transmit a tone of known frequency to surface module controller **125**. Controller **125** receives the signal at step **502**, samples the received signal and applies a Fast Fourier transform (FFT) to determine the magnitude of the known frequency in the received signal at step **503**. If the mean frequency magnitude is less than a predetermined threshold the PGA (Programmable Gain Amplifier) gain is adjusted to increase the signal amplitude. The gain to be applied is determined by indexing a preset PGA table.

The magnitude of the frequency and gain applied are stored in a results table at step **5-5**. This sequence is repeated for different frequencies across a desired channel bandwidth range. At step **507** the stored results are used to determine analogue filter settings to be applied by the analogue adaptive equalisation control module **411** for each filter stage.

A filter stage's frequency response can be controlled by Controller **125**. The controller **125** calculates the optimum

For all possible combinations of filter switch settings and frequencies, the cumulative filter frequency response is added to the observed frequency response and stored in a results table.

An exemplary implementation of this is shown in FIG. **5** where each filter setting is selected in turn at step **601**, each frequency is selected in turn at step **602**. The cumulative filter frequency response of the filter settings selected is calculated at step **603** by summing the responses of each stage. The resulting response is determined at step **604** by adding the observed frequency response to the cumulative filter frequency response and stored in a results table for processing.

In the embodiment shown filter stages **1** to **6** are controlled by three switches, filter stage **7** is controlled by two switches and filter stage **8** is controlled by four switches. A 24 bit value representing the setting for all 8 stages may conveniently be represented as a 6 hexadecimal digits.

So, for example, if the observed frequency response at 10 KHz is 56.5341 dB and the cumulative filter frequency response for filter stage setting 456DB6 (binary 0100 0101 0110 1101 1011 0110) is 1.3397 dB then the resulting frequency response determined and stored in the results table at step **604** for 10 KHz would be 57.8738.

An example of a data from the results table after each resulting frequency response has been determined for filter setting 456DB6 might be:

	kHz								
HEX	10	15	20	25	30	35	40	45	50
456DB6	57.8738	56.7738	54.2734	57.3562	53.8741	54.8778	57.8596	57.8733	54.8732

	kHz							
HEX	55	60	65	70	75	80	85	90
456DB6	55.6777	55.4432	56.8768	56.8763	54.5768	57.8768	58.8778	59.8878

Once the resulting frequency responses for all possible filter settings at each of the predetermined frequencies have been calculated and stored, a standard deviation of the resulting frequency responses for a given setting is determined at step **607** (in the above example the standard deviation is 1.73699) to measure the variability of the responses across the frequency range. It is desirable to select the filter settings giving the least variable or 'flattest' response.

The filter settings providing the optimum response are determined at step **608** by selecting the filter setting having the lowest standard deviation in the resulting frequency responses

The controller **125** then sends command to **115** to stop tuning mode. The modem then re-initialises for data transmission.

Autotuning can be done automatically at tool power on to tune to cable in use or at any time by user request—to improve the channel frequency response, for example when several thousand feet of cable have been spooled out which can often alter the CFR, the AFE can be retuned.

The bandwidth of the AFE defaults to a fixed width. Depending upon the auto-tuning results the system can automatically increase the AFE filter bandwidth allowing the modem to provide higher data rates, for example, 300 Kbits/s.

When cable CFR is poor, the bandwidth may also be reduced to maintain reliable communication albeit at lower data rates.

Quadrature amplitude modulation (QAM) codes two digital bit streams, by modulating the amplitudes of two carrier waves. The two carrier waves, are usually sinusoidal and are out of phase with each other by 90°. The carrier waves are usually referred to as an 'inphase' and 'quadrature' carriers and the components are often referred to as the 'I' component and the 'Q' component respectively.

In digital QAM, a finite number of at least two phases and at least two amplitudes are used.

A useful representation of QAM modulation scheme is the constellation diagram which is a pictorial representation of a mapping showing how each symbol is coded by the inphase and quadrature carriers. Examples of constellation diagrams are shown in FIGS. **7***a* to **7***d*.

Referring to FIGS. **7***a* to **7***d* it will be appreciated that the symbols represented by the 'outer' points in the constellation will have better signal to noise ratio than signals closer to the origin because those symbols are represented by carrier signals having a greater amplitude. For example symbols labelled **901** in FIG. **7***a* will have the greatest signal to noise ratio in 8QAM.

Symbols represented by points on the axis of the constellation are represented by a pure sinusoidal signal (again points labelled **901** in FIG. **7***a*), signals represented by points on the diagonal will be represented by signals having equal inphase and quadrature components, these points are labelled **902** in FIG. **7***a*.

Upon reception of the signal, the demodulator examines the received symbol, which may have been corrupted by the channel or the receiver (e.g. additive white Gaussian noise, distortion, phase noise or interference). It selects, as its estimate of what was actually transmitted, that point on the constellation diagram which is closest (in a Euclidean distance sense) to that of the received symbol. Thus it will demodulate incorrectly if the corruption has caused the received symbol to move closer to another constellation point than the one transmitted.

High spectral efficiencies can be achieved with QAM by setting a suitable constellation size, limited only by the noise level and linearity of the communications channel.

On shorter cable lengths, with good CFR or longer cables with exceptional CFR. QAM32 or QAM64 encoding can be employed to increase the data rate without extending bandwidth. Higher rates are possible with extended bandwidth, e.g. 300 to 400 Kbits/s. This can be selected dynamically e.g. whilst tool is running and/or deployed.

Because the probe has to fit in relatively narrow pipelines, the telemetry module **11** is implemented on a circuit board with a max width of 30 mm to fit into the inspection apparatus. This means that the module must be designed to make the components as small as possible in order to fit within the necessary size limitations.

The operation of the QAM receiver **121** will now be described in more detail with reference to FIG. **6** which illustrates schematically a QAM receiver. A carrier recovery loop **20** generates replicas of the QAM quadrature carriers.

The phase of these carriers must be synchronised with the received signal r(n). Received signal r(n) is multiplied by quadrature carrier signals cos θ and sin θ to generate observed symbol values X(n) and Y(n). Slicer **21** maps the observed X(n) and Y(n) to the closest (in the Euclidean sense) constellation values I(n) and Q(n). Phase detector **22** determines the phase difference between X(n),Y(n) and I(n),Q(n).

The phase difference detected is sent to a loop filter **23** and the output is then used to adjust the phase of the carrier signals generated by a direct digital synthesiser **24**.

One method of determining the phase difference between two quadrature encoded signals is to determine the phase of each signal using the arctangent function and then calculate the difference between the two resulting phase angles. The arctangent function may be implemented by using a look up table, but this uses a large amount of memory. The present invention provides an improved technique for determining the phase error.

The complexity of the calculation may be reduced by using the fact that for small $\Delta\phi$ the phase difference $\Delta\phi(n)$ is proportional to $I(n)Y(n)-Q(n)X(n)$.

The method of achieving phase lock is illustrated in FIG. **8**.

In the present invention a coarse phase lock is achieved by transmitting a sine wave, preferably representing a symbol having the greatest amplitude modulating components and therefore the greatest signal to noise ratio. In the preferred embodiment this signal represents a symbol lying in the first quadrant and represents a data stream of '1's.

The preamble is received by the surface module controller at step **701**.

The phase error is calculated by phase detector **22** using the result of the above cross product calculation and accessing a lookup table (LUT) comprising 18 locations of 16 bit data.

The 18 memory locations in the LUT are used to determine the phase error from pre-calculated values of I(n)Y(n)−Q(n)X(n).

Since we know that ideal symbol position (in first quadrant and in rightmost corner) then if the received symbol falls in any one of the other three quadrants (determined by the sign of the measured Symbols X(n) and Y(n)) the signal is firstly coarsely phase adjusted by 90, 180 or 270 degrees respectively at step **702**. This makes it possible to use a reduced look up table because only adjustments in a single quadrant are required.

At step **705** the cross product I(n)Y(n)−Q(n)X(n) is calculated. A phase adjustment is determined at step **706** using the LUT shown below using the value from the LUT which is closest to the cross product I(n)Y(n)−Q(n)X(n).

ABS[I(n)Y(n) − Q(n)X(n)]	Phase Error (Degrees)
1080	0.5
2160	1
4080	2
6000	3
8160	4
9840	5
12000	6
14160	7
16080	8
18000	9
20160	10
29760	15
39360	20
48720	25
57600	30
66240	35
74160	40
81600	45

The phase adjustment is sent to the loop filter **23** at step **706** which sends a signal to the digital signal synthesiser **24** to adjust the generated replica carrier signals accordingly.

The signals are iteratively adjusted until the phase error is less than a predetermined minimum threshold at step **707**, in the preferred embodiment the predetermined minimum threshold is set to 0.5 degrees.

It is possible to use a sparse table which does not contain entries for every value of the cross product to reduce the memory requirements by having index entries which are closer together for small phase difference and further apart for greater phase differences. In this way when the phase difference is greater, the phase adjustment applied is unlikely to result in a signal which matches the phase precisely, but that will be improved on further iterations.

Because large temperature differences cause large frequency deviations a similar technique can be used to lock on to the transmitted carrier frequency. A method of maintaining frequency lock is illustrated in FIG. **9**.

After achieving the phase lock the constellation will rotate (clock wise or anti clockwise) due to carrier frequency differences between the transmitter **111** and the receiver **121**. This rotation and the direction of rotation can be monitored by measuring the symbols which should have equal observed X and Y values. When these symbols rotate, there will be a difference between the magnitudes of the X and Y components. By monitoring this difference over number of received symbols we can estimated the magnitude and direction of rotation.

The average difference between the magnitudes can be monitored. In a preferred embodiment a count of the polarity of the difference is maintained as follows:

If I is approximately equal to Q at step **802** then a phase count variable is updated at step **803** according to the following equation:

```
If I > Q then
  IQ_PhaseCount = IQ_PhaseCount − '1';
Else
  IQ_PhaseCount = IQ_PhaseCount + '1';
End If;
```

In the preferred embodiment of the present invention the phase is adjusted by half a degree if the phase count becomes greater than a predetermined threshold which is preferably set to fifteen.

If the constellation is not rotating then the phase differences will fluctuate around zero and the phasecount variable will not exceed the predetermined threshold. In the event the threshold is exceeded at step **804** a small phase adjustment is applied and the phase count variable is reset to zero.

In different embodiments of the invention the magnitude of the phase adjustments may be set to 0.5, 1 or 2 degrees to counter that rotation.

This is a continuous process and dynamic frequency matching is achieved by adjusting the phase of the carrier.

It is appreciated that certain features of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the invention which are, for brevity, described in the context of a single embodiment, may also be provided separately, or in any suitable combination.

It is to be recognised that various alterations, modifications, and/or additions may be introduced into the constructions and arrangements of parts described above without departing from the scope of the present invention as defined in the following claims.

The invention claimed is:

1. A method of receiving data from a telemetry module, the data being modulated according to a quadrature amplitude modulation coding scheme, in which a receiver has a carrier recovery circuit comprising a phase detector, a loop filter and a signal synthesiser generating an inphase and a quadrature demodulation signal, the method comprising the steps of:

a) receiving a preamble sinusoidal signal representing a symbol;

b) matching a phase of the inphase signal generated by the signal synthesiser to a phase of the received signal;

c) matching a phase of the quadrature signal generated by the signal synthesiser to be ninety degrees out of phase the phase with the received signal;

d) repeating a step of determining whether the received signal represents a symbol having positive inphase and quadrature components; in the event the inphase and quadrature components of the received signal are not both positive, adjusting the phase of the inphase and quadrature components by a fixed phase shift until the received signal represents a symbol having positive inphase and quadrature components;

e) determining a cross product of the received inphase and quadrature components and ideal inphase and quadrature components;

f) indexing a look up table with said cross product to determine a phase adjustment;

g) adjusting the phase of the demodulation signals in accordance with said determined phase adjustment and further comprising adjusting for small phase rotations due to frequency fluctuations by

h) determining whether the received signal represents a symbol having equal inphase and quadrature components;

i) in the event the received signal represents a symbol having equal inphase and quadrature components, updating a phase difference measure in dependence upon the difference between the magnitude of the inphase and quadrature component of the received signal; and

j) adjusting the phase of the signals generated by the signal synthesiser when said phase difference measure exceeds a predetermined threshold.

2. The method according to claim **1**, further comprising repeating steps e) to g) until the phase adjustment is less than a predetermined minimum.

3. The method according to claim **2**, in which said predetermined minimum is 0.5 degrees.

4. The method according to claim **1**, in which the preamble signal is a sinusoidal signal representing a symbol in the encoding scheme having the greatest signal to noise ratio.

5. The method according to claim **1**, in which the lookup table comprises entries for unequally spaced phase differences with entries close together for small phase differences and entries further apart for greater phase differences.

6. The method according to claim **1**, in which the phase difference measure is updated at step i) by incrementing the phase difference measure by one if a first one of the components is greater than a second one of the components and by decrementing the phase difference measure by one if the second one of the components is greater that the first one of the components.

7. The method according to claim **6** in which the predetermined threshold is fifteen.

8. The method according to claim **1**, in which the phase is adjusted by step j) by 0.5 degrees when said phase difference measure exceeds a predetermined threshold.

9. An apparatus for receiving data from a telemetry module comprising a receiver having a carrier recovery circuit comprising a phase detector, a loop filter and a signal synthesiser generating an inphase and a quadrature demodulation signal in which the receiver is arranged in operation to

a) receive a preamble sinusoidal signal representing a symbol;

b) match a phase of the inphase signal generated by the signal synthesiser to a phase of the received signal;

c) match a phase of the quadrature signal generated by the signal synthesiser to be ninety degrees out of phase the phase with the received signal;

d) repeat a step of determining whether the received signal represents a symbol having positive inphase and quadrature components; in the event the inphase and quadrature components of the received signal are not both positive, adjusting the phase of the inphase and quadrature components by a fixed phase shift until the received signal represents a symbol having positive inphase and quadrature components;

e) determine a cross product of the received inphase and quadrature components and ideal inphase and quadrature components

f) index a look up table with said cross product to determine a phase adjustment and

g) adjust the phase of the demodulation signals in accordance with said determined phase adjustment and in which the receiver is further arranged in operation to adjust for small phase rotations due to frequency fluctuations by

h) determining whether the received signal represents a symbol having equal inphase and quadrature components;

i) in the event the received signal represents a symbol having equal inphase and quadrature components, updating a phase difference measure in dependence upon the difference between the magnitude of the inphase and quadrature component of the received signal; and

j) adjusting the phase of the signals generated by the signal synthesiser when said phase difference measure exceeds a predetermined threshold.

10. The apparatus according to claim **9**, in which the receiver is arranged in operation to repeat steps e) to g) until the phase adjustment is less than a predetermined minimum.

11. The apparatus according to claim **10**, in which said predetermined minimum is 0.5 degrees.

12. The apparatus according to claim **9**, in which the preamble signal is a sinusoidal signal representing a symbol in the encoding scheme having the greatest signal to noise ratio.

13. The apparatus according to claim **9**, in which the lookup table comprises entries for unequally spaced phase differences with entries close together for small phase differences and entries further apart for greater phase differences.

14. The apparatus according to claim **9**, in which the phase difference measure is updated at step i) by incrementing the phase difference measure by one if a first one of the components is greater than a second one of the components and by decrementing the phase difference measure by one if the second one of the components is greater that the first one of the components.

15. The apparatus according to claim **14** in which the predetermined threshold is fifteen.

16. The apparatus according to claim **9**, in which the phase is adjusted by step j) by 0.5 degrees when said phase difference measure exceeds a predetermined threshold.

* * * * *